Experimental Visualization of Ion Thruster Discharge and Beam Extraction

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To inspect numerical models for precise numerical analysis code development and to research ion thruster mechanisms (its discharge and ion beam optics behavior), a two-dimensional Kaufman-type visualized ion thruster was designed and fabricated. Its operations, probe measurements and spectroscopy measurements indicate that this thruster can visualize a schematic of ion production and extraction as described in conventional textbooks: ion beam extraction influences the ion density distribution in most of the discharge chamber; a close correlation exists between the ion beam focus position and the appropriate beam optics.

Key Words: Ion Thruster, Visualization, Magnetic Field, Kaufman-type Ion Source

Nomenclature

\[
\begin{align*}
  d & : \text{distance} \\
  I & : \text{current} \\
  n & : \text{number density} \\
  T & : \text{temperature} \\
  V & : \text{potential} \\
  Z & : \text{position} \\
\end{align*}
\]

Subscripts

\[
\begin{align*}
  a & : \text{acceleration grid (Ac)} \\
  b & : \text{beam} \\
  e & : \text{electron} \\
  f & : \text{focus} \\
  p & : \text{plasma} \\
  s & : \text{screen grid (Sc) or sheath} \\
\end{align*}
\]

1. Introduction

Many ion thrusters are installed in various satellites: geostationary orbit satellites, space probes, etc. Because ion thrusters are gaining recognition as space propulsion systems through their actual use, they are expected to increase in number and variety. A durable ion thruster with operational life of more than a few years is anticipated as an attractive thruster for future use because a durable thruster is needed for deep space probes and long-term operational satellites. Durable thruster development requires precise numerical analysis to confirm its durability because experimental confirmation demands high costs and a long time. Many numerical analyses have been studied as design aids for ion thrusters \(^{1-7}\). Nevertheless, numerical analysis codes have not been completed. Reasons include the greater difficulty of a numerical model inspection than experimentation.

Therefore, a two-dimensional visualized ion thruster was developed to contribute to inspections of precise numerical analysis code not only with conventional methods of current and voltage measurements but also with other methods of noncontact optical measurements. Furthermore, the thruster is shown in a two-dimensional schematic of an ion thruster shown in Fig. 1; it can contribute to fundamental understanding of the ion thruster mechanism and ion beam optics behavior, as presented in Fig. 2 \(^{8-10}\). The objectives of this study are (1) design and fabrication of the visualized ion thruster (VIT) with a conventional magnetic field, and (2) thruster evaluation.

2. Thruster Design

2.1. Ion Source

As depicted in Fig. 3, the VIT is a two-dimensional rectangular parallelepiped \(^{11}\).
Plasma is produced by direct current discharge: the VIT is an electron-bombardment-type thruster. The discharge chamber wall comprises a pair of L-shaped iron yokes, a pair of rectangle glass plates, and a rectangular stainless steel grid system. The discharge chamber dimensions are $80 \times 50 \times 80$ mm. The yokes are set for the magnetic field formation; the glass plates are set for the spectroscopic measurements. Three pairs of rectangular stainless steel anodes are set within the discharge chamber. Changing the electrical connection to one anode or all anodes alters the discharge path. An electron source exists at the center of the upstream discharge chamber wall. The electron is produced by a filament within the source. It is emitted to the discharge chamber through the keeper bridge plasma. The xenon propellant particle flows into the chamber through the electron source. It is ionized by the electron bombardment and extracted by the grid system.

2.2. Grid System

The grid systems of VIT comprise two grids in this study. Each grid has three narrow slits in the y-direction. Table 1 presents the grid systems parameters for S3GS and S6GS. The S6GS is only used in the evaluation of the magnetic field. The screen grid is fixed to the discharge chamber; the acceleration grid is fitted to the discharge chamber with four stainless steel springs and four ceramic screws to maintain the gap. The slits of the viewer’s side (in the +y-direction) were canaliform machined, as depicted in Fig. 3, to observe most ion beam optics. The remaining thickness is 0.2 mm. The slit grid system extracts three sheet-shaped ion beams. A viewer can observe three bright ion beams if seen from the +y-direction.

<table>
<thead>
<tr>
<th>Grid system parameter</th>
<th>S3GS (mm)</th>
<th>S6GS (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sc-grid slit width</td>
<td>3.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Sc-grid thickness</td>
<td>1.5</td>
<td>3.0</td>
</tr>
<tr>
<td>Ac-grid slit width</td>
<td>2.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Ac-grid thickness</td>
<td>1.5</td>
<td>3.0</td>
</tr>
<tr>
<td>Grid slit length</td>
<td>30.0</td>
<td>30</td>
</tr>
<tr>
<td>Grid slit pitch</td>
<td>5.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Grid gap</td>
<td>0.8</td>
<td>1.6</td>
</tr>
</tbody>
</table>

2.3. Magnetic Field and Baffle

A diffusion-type (Kaufman-type) magnetic is adopted as the VIT magnetic field because of its small discharge chamber. Figure 4 depicts a schematic of the magnetic field, baffle, and primary electron flow. This magnetic field was formed using some Sm-Co permanent magnets. The baffle was set directly at the exit plate of electron source for inclination of the emitted electron flow. The primary electrons emitted from the electron source are inclined to the magnetic force lines by the baffle. They flow spirally into one anode plate. The VIT with these items are as presented in Table 2. The BM-VIT corresponds to a conventional Kaufman-type ion thruster.

<table>
<thead>
<tr>
<th>Table 2. VIT series name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>N-VIT</td>
</tr>
<tr>
<td>B-VIT</td>
</tr>
<tr>
<td>M-VIT</td>
</tr>
<tr>
<td>BM-VIT</td>
</tr>
</tbody>
</table>

3. Experimental Procedure and Apparatus

3.1. VIT Operation

A schematic of the electric circuit for this experiment is depicted in Fig. 3. The screen grid is connected electrically to the discharge chamber. All anode potentials are equal. The VIT operates at the following conditions: $0.30–0.90$ sccm (0.15 sccm step) propellant flow rate, 50 V discharge voltage, 0.45 A total discharge current, and 0.10 A keeper current, with 40 V keeper voltage at the off-discharge condition. The voltage instantly decreases to ca. 0 V because of the constant current control at the on-discharge condition. The screen grid potential is 0–2 kV; the acceleration grid potential is -200 V. These currents and potentials are applied with errors of 1%. The propellant flow rate control error is less than ca. 1%. The vacuum pressure is ca. 3 mPa when the xenon flow rate is 0.60 sccm (60 $\mu$g/s, Xe).
3.2. Probe Measurements
A 0.20-mm-diameter pure tungsten wire that is almost covered with a 1.0-mm-diameter ceramic tube is used as a Langmuir probe. The exposed length is 0.08 mm. This probe is inserted to the discharge chamber through a small hole in the glass plate; it is moved in the y-direction to undisturb the plasma production. The location error is less than 1 mm in all directions. The reference potential of this probe is as high as the discharge chamber wall potential: the screen grid potential. Probe measurements are done using N-VIT operation in a non-extraction condition.

3.3. Spectroscopic Measurements
To divide the measurement area, a lattice of square pipes is arranged between the VIT glass plate and a glass porthole of the vacuum chamber, with little clearance. The location error is less than 0.5 mm in each direction. The divided light is detected using a spectrometer via a fiber-optic cable. To correct the spectroscopic intensity of each area, a spatially uniform light was detected as the reference in preliminary experiment. All measured spectroscopy intensity was compensated with the correction factor derived from results of this preliminary experiment.

4. Results and Discussion

4.1. Experimental Visualization
Figure 5 depicts the discharge plasma and three ion beams observed directly through the VIT glass plate. The slightly bright line at the right of grid system is the plasma light reflected by the glass plate edge. As described in detail hereinafter, the plasma sheath near the grid system was also observed clearly. The VIT can visualize the schematic of ion production and extraction, as presented in Fig. 1.

4.2. Discharge Plasma Uniformity
The distribution of electron number density at a point near the grid system is depicted in Fig. 6. The reproducibility error ratio is ca. 5% at most measurement points. As presented in this figure, the density is almost uniform in the y-direction. It was confirmed that the discharge had near uniformity in the y-direction, excluding the near area of the keeper plasma emission hole. The electron number density and electron temperature are ca. $8.4 \times 10^{12}$ cm$^{-3}$ and 3 eV, respectively. The plasma space potential in this uniform region is 52–54 V, which is 2–4 V higher than the anode potential.

![Figure 5 N-VIT in operation](image)

![Figure 6 Discharge plasma uniformity in y-direction](image)

4.3. Discharge Plasma in the Magnetic Field
Figure 7 shows the discharge plasma of the N-, B-, M-, and BM-VIT. This figure implies that the baffle inclines the primary electrons flow to the magnetic force lines, and that the ionization occurs along the magnetic force lines. Table 3 presents the performance and operational conditions of the VIT series. This table shows that both the baffle and magnetic field improve the performance and expand the operational perveance range because the screen current is associated with the plasma density near the grid system. The B-VIT has a narrow operational range because of the flow rate. The baffle affects ionization in the low flow rate condition.

Because the VIT can visualize the discharge plasma in the magnetic field with the baffle experimentally, as shown in Figs. 1 and 4, the VIT contributes to the fundamental understanding of an ion source thruster with a magnetic field, especially the Kaufman-type ion thruster.

Table 3. VIT series performance

<table>
<thead>
<tr>
<th>parameter</th>
<th>unit</th>
<th>N-</th>
<th>B-</th>
<th>M-</th>
<th>BM-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow rate</td>
<td>sccm</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Filament power</td>
<td>W</td>
<td>13.4</td>
<td>16.0</td>
<td>14.5</td>
<td>14.5</td>
</tr>
<tr>
<td>Discharge power</td>
<td>W</td>
<td>22.5</td>
<td>22.5</td>
<td>22.5</td>
<td>22.5</td>
</tr>
<tr>
<td>Sc-grid potential</td>
<td>kV</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Ac-grid potential</td>
<td>V</td>
<td>-200</td>
<td>-200</td>
<td>-200</td>
<td>-200</td>
</tr>
<tr>
<td>Sc-grid current</td>
<td>mA</td>
<td>2.1</td>
<td>3.4</td>
<td>6.7</td>
<td>7.4</td>
</tr>
<tr>
<td>Ac-grid current</td>
<td>mA</td>
<td>0.17</td>
<td>0.22</td>
<td>0.58</td>
<td>0.63</td>
</tr>
<tr>
<td>Beam current</td>
<td>mA</td>
<td>1.9</td>
<td>3.2</td>
<td>6.1</td>
<td>6.8</td>
</tr>
<tr>
<td>operational condition</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Min. flow rate</td>
<td>sccm</td>
<td>0.45</td>
<td>0.75</td>
<td>0.45</td>
<td>0.60</td>
</tr>
<tr>
<td>Pervane e per slit</td>
<td>min</td>
<td>nAV$^{-1.5}$</td>
<td>7.8</td>
<td>12</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>nAV$^{-1.5}$</td>
<td>84</td>
<td>130</td>
<td>310</td>
</tr>
</tbody>
</table>
Figure 7 Discharge plasmas of VIT series

(a) N-VIT
(b) B-VIT
(c) M-VIT
(d) BM-VIT

Figure 8 Ion beam extraction influence (N-VIT)

Figure 9 Ion beam optics
4.4. Beam Extraction

Figure 8 depicts the ratio of ion luminescence intensity (467 nm) when ions were extracted using 1 kV (upper half) and 2 kV (lower half) screen grid potential, to that when ions were not extracted. The data presented therein suggest that ion beam extraction influences the ion density distribution in most of the discharge chamber, not only near the grid system. Therefore, it is necessary that the more precise numerical analysis of ion beam extraction simulate the wide-ranging influence of ion density distribution or plasma production in the discharge chamber.

Figure 9 presents photographs of the plasma sheath and ion beam for some screen grid potential cases. The plasma sheath profile near the grid slit becomes convex when the screen grid potential is set at 0 kV; the sheath profiles become concave when the screen grid potential is set at 1 kV or 2 kV. The ion beam impinged to the acceleration grid when the screen grid potential was set to greater than 1.25 kV. This phenomenon agrees well with the change of acceleration grid current against the screen grid potential, as presented in Fig. 10. Furthermore, because the screen grid potential is higher, the concave sheath is larger and the beamlet focus position is toward the screen grid from the acceleration grid on the center axis. This can be reasonably explained by Child law sheath formation:

\[ d_s \propto n_p^{1/2} T_e^{-1/4} V_s^{3/4} \]  

where \( d_s \), \( n_p \), \( T_e \), and \( V_s \) respectively signify the sheath thickness, the plasma number density, the electron temperature of plasma and the screen grid potential. This relation is derived from the space charge limitation current density and the ion saturation current density with an assumption of one-dimensional ion flow. Actually, Fig. 2 is based on this relation. This experimental visualization of the VIT grid system is useful for fundamental understanding of ion beam optics behavior.

Figure 11 portrays the position of the focus position (\( Z_f \)) and the sheath edge position on the center axis (\( Z_s \)) against the screen grid potential. This phenomenon agrees well with the change of acceleration grid current against the screen grid potential, as presented in Fig. 10. Furthermore, because the screen grid potential is higher, the concave sheath is larger and the beamlet focus position is toward the screen grid from the acceleration grid on the center axis. This can be reasonably explained by Child law sheath formation:

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These positions are the distance from the center of screen grid upstream surface. Sheath edge points were determined roughly from low-grade high-contrasted photographs. This figure shows that the focus position of ion beam is moved by the screen grid potential (the net acceleration voltage). In ion beam optics studies, this point deserves emphasis.

Figure 12 depicts the distance between the focus point and the sheath edge point ($Z_f - Z_e$) against the screen grid potential with the change of the acceleration grid drain current ratio. As described above, with one-dimensional ion beam flow, this distance corresponds to the sheath thickness.

Figure 13, redrawn with these figures, shows the screen grid potential and the acceleration grid drain current ratio against the beamlet focus position. These figures suggest that (1) both the focus position and the sheath edge position are moving upstream as the screen grid potential is higher, (2) the distance between the focus point and the sheath edge point is almost constant when the ion beam impinged to the acceleration grid, and (3) the ion beam impinges to the acceleration grid when the beamlet focus position is in the gap separating the screen and acceleration grid. Although it is necessary to investigate whether these phenomena are general or particular in this grid system, it is convenient to infer that the close correlation between the positions and the appropriate ion beam optics was confirmed.

Little attention has been given to the visualization of ion beam optics as an evaluation method for ion thrusters. These results and discussion therefore contribute greatly to the development of numerical analysis codes for estimation of ion thruster durability, for inspection of numerical analysis models.

5. Summary

The probe and spectroscopy measurements of a two-dimensional visualized ion thruster operation presented here, along with comparative evaluation of experimental data and simulated results for plasma sheath profiles and ion beam focus position, contribute to the development of a numerical analysis code that can simulate ion thruster durability precisely. Furthermore, the discharge plasma in a Kaufman-type magnetic field with a baffle was observed. This thruster can represent a well-known schematic described in some conventional textbooks, Kaufman-type ion thruster. It is useful for the fundamental illustration of an ion thruster mechanism and ion beam optics behavior.

References


